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PHENOMENOLOGY OF LIGHT STERILE NEUTRINOS: A BRIEF REVIEW

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An increasing number of anomalous experimental results are emerging, which cannot be described within the standard 3-neutrino framework. We present a concise discussion of the most popular phenomenological interpretation of such findings, based on a hypothetical flavor conversion phenomenon of the ordinary “active” neutrinos into new light “sterile” species having mass $m \sim \mathcal{O}(1)$ eV.

Keywords: Neutrino oscillations; sterile neutrinos.

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1. Introduction

A long series of neutrino oscillation experiments performed in the last two decades has established that neutrinos are massive and mix. In the standard 3-flavor framework the three flavor eigenstates (ν_e, ν_μ, ν_τ) mix with three mass eigenstates (ν_1, ν_2, ν_3) through a unitary matrix entailing three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one CP-violating phase δ . All the three mixing angles are now known to be different from zero ($\theta_{12} \simeq 34^\circ$, $\theta_{23} \simeq 39^\circ$ and $\theta_{13} \simeq 9^\circ$), while the preferred value of the CP-violating phase lies around $\delta \simeq \pi$, although with low statistical significance [1]. In the 3-flavor scheme the neutrino oscillations are driven by two independent mass-squared differences, $\Delta m_{12}^2 = m_2^2 - m_1^2 \simeq 7.5 \times 10^{-5} \text{ eV}^2$ (known as the “solar splitting”) and $|\Delta m_{13}^2| = |m_3^2 - m_1^2| \simeq 2.4 \times 10^{-3} \text{ eV}^2$ (dubbed as the “atmospheric splitting”). The neutrino mass hierarchy (i.e. the sign of Δm_{13}^2) is currently unknown and, together with the CP-violating phase δ , is at the center of an intense campaign of new experimental searches.

While the standard 3-flavor framework has been solidly established as the only one able to describe the huge amount of information coming from solar, atmospheric, reactor and accelerator neutrino experiments, a few “anomalous” results have emerged in very-short-baseline (VSBL) neutrino oscillation measurements and in cosmological data analyses, which cannot be accommodated in such a scheme. The most popular interpretation of such anomalies is based on a simple extension

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of the 3-flavor paradigm, involving new additional light neutrinos (with mass in the eV range) which mix with the ordinary neutrinos. From the LEP measurement of the invisible decay width of the Z boson [2], we know that there are only three light (with mass below one half of the Z boson mass) neutrinos which couple to the Z boson. Therefore, the new putative light neutral fermions must be “sterile”, i.e. singlets of the Standard Model gauge group, to be contrasted with the ordinary “active” neutrino species, which are members of weak isospin doublets.

From a theoretical standpoint, it seems natural to expect the existence of such new gauge singlets as they appear in many extensions of the Standard Model. Indeed, the most popular models of neutrino mass-generation, the so-called see-saw mechanisms, normally involve sterile neutrinos. Although the majority of such extensions entail sterile neutrinos with mass close to the grand unification scale or the TeV scale, *a priori* there is no theoretical constraint on the mass of these particles. In fact, several models have been investigated in which much lighter sterile neutrinos arise (see the overview given in [3]). In essence, the theory only tells us that sterile neutrinos *can* exist, without giving any certain information on their number and their mass-mixing properties, which ultimately have to be determined by the experiments.

From a phenomenological perspective, the sterile neutrinos must be introduced without spoiling the basic success of the standard 3-flavor framework. This can be achieved in the so-called $3 + s$ schemes, where s new mass eigenstates are assumed to exist, separated from the three standard ones by large mass splittings, with a hierarchical spectrum $|\Delta m_{12}^2| \ll |\Delta m_{13}^2| \ll |\Delta m_{1j}^2| (j = 4, \dots, 3 + s)$. This ensures that the oscillations induced by the new mass-squared differences are completely averaged in the experimental setups sensitive to Δm_{12}^2 -driven (solar) and Δm_{13}^2 -driven (atmospheric) transitions, leaving unaltered the well-established frequencies of the standard oscillation processes. With the additional assumption that the admixtures among the actives flavors and the new mass eigenstates (ν_4, \dots, ν_{3+s}) are small ($|U_{ej}|^2, |U_{\mu j}|^2, |U_{\tau j}|^2 \ll 1, j = 4, \dots, 3 + s$) [or equivalently that the new neutrino mass eigenstates are mostly sterile ($|U_{s4}|^2, \dots, |U_{s,3+s}|^2 \simeq 1$)], the $3 + s$ schemes leave almost untouched also the standard oscillation amplitudes.

In such a way, the $3 + s$ frameworks realize a peculiar enlargement of the standard 3-flavor scheme, as they induce strong effects in those setups where the anomalies show up, while having only a small (but different from zero) impact on the “ordinary” pieces of data commonly used for the 3-flavor global fits. However, we underline that, at the present level of accuracy one must take into account both the leading effects normally expected in VSBL experiments and the small ones expected in the ordinary setups.

In what follows we concisely describe the anomalous results and discuss their mutual (in-)consistency. We also provide a concrete example of how some “ordinary” pieces of data, namely the solar neutrino sector experiments together with the new dual-baseline θ_{13} -sensitive reactor experiments Daya Bay and RENO, are able to

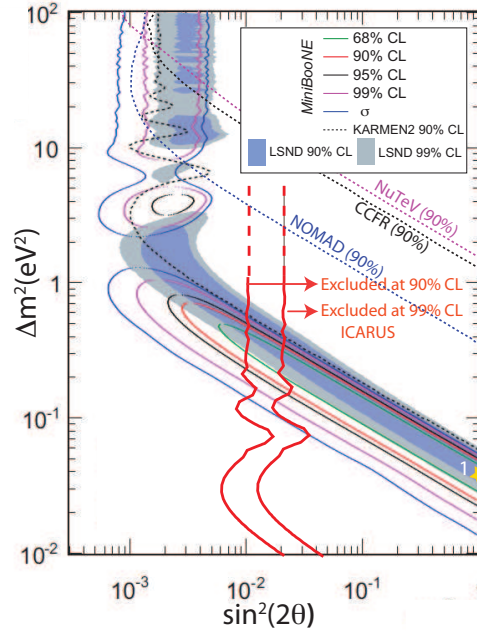


Fig. 1. Regions allowed by the main published experiments sensitive to the accelerator anomaly superimposed to the limits established by the ICARUS experiment. Figure taken from [9].

put interesting constraints on the 3+1 scheme. Finally we draw our conclusions.

2. The anomalies

2.1. The accelerator anomaly

Accelerator experiments with baselines L of few tens of meters and neutrino energies E_ν of a few tens of MeV ($L/E_\nu \sim 1$ m/MeV) are sensitive probes of neutrino oscillations potentially occurring at $\Delta m^2 \sim 1$ eV². Their results are commonly interpreted in terms of a new mass-squared difference Δm^2 and of an effective mixing angle θ . In a 3+1 framework the following identifications hold: $\Delta m^2 \equiv \Delta m_{14}^2$ and $\sin^2 2\theta \equiv 4|U_{e4}|^2|U_{\mu 4}|^2$.

In fact, the anomalous result recorded at the LSND accelerator experiment [4, 5] was the first piece of data pointing towards light sterile neutrinos. Such an experiment, designed to study $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions, evidenced an excess of electron antineutrino events at the $\sim 3.8\sigma$ level [5]. The mass-mixing regions preferred by LSND are depicted in Fig. 1 as colored bands.

The experiment KARMEN [6], which is very similar to LSND, observed no such a signal, but could not rule out all the mass-mixing parameter regions allowed by LSND, as shown in Fig. 1, where the region excluded by KARMEN is delimited by the dashed gray line. In particular, due to the smaller baseline (17.5 m vs 30 m)

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KARMEN could not exclude values of $\Delta m^2 < 2 \text{ eV}^2$ also leaving marginal room for a solution at $\Delta m^2 \sim 7 \text{ eV}^2$ (see the combined analysis of LSND and KARMEN performed in [7]).

The experiment MiniBooNE, designed to test the LSND anomaly, and sensitive both to $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions, has given differing results during the last few years. According to the latest data release [8] (differently from the past) MiniBooNE seem to lend support to the longstanding LSND anomaly. As a matter of fact, a combined analysis of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channels evidences an excess in the range $200 < E_\nu < 1250 \text{ MeV}$ at the $\sim 3.8\sigma$ level. The mass-mixing regions compatible with this result are shown as colored contours in Fig. 1. It must be noted that most of the signal comes from the low-energy region $E_\nu < 475 \text{ MeV}$ (not included in some of the previous analyses performed by the MiniBooNE collaboration), where the background evaluation is particularly problematic.

An independent test of the LSND and MiniBooNE anomalies has been recently performed at the long-baseline accelerator experiment ICARUS [9]. This novel test has been possible because in the ICARUS setup, due to the high energy of the beam ($< E_\nu > \sim 17 \text{ GeV}$), the 3-flavor effects induced by non-zero θ_{13} play a negligible role. As a result, the experiment is sensitive to sterile neutrino oscillations, which due to the high value $L/E_\nu \sim 36.5 \text{ m/MeV}$ get completely averaged, and appear as an energy independent enhancement of the expected rate of events. However, ICARUS is not sensitive enough to rule out all the relevant mass-mixing region, and could only restrict the allowed region to values of $\sin^2 2\theta \lesssim 10^{-2}$, as shown in Fig. 1. From the same plot one can qualitatively infer that the combination of the four experiments LSND, KARMEN, MiniBooNE and ICARUS, restricts the allowed mass-mixing parameters to a small region centered around ($\Delta m^2 \sim 0.5 \text{ eV}^2$, $\sin^2 2\theta \sim 5 \times 10^{-3}$).

2.2. The reactor and gallium anomalies

The new refined calculations of the reactor antineutrino spectra recently performed in [10, 11] have provided the main driving force for the renewed interest into light sterile neutrinos. These calculations indicate fluxes which are $\sim 3.5\%$ higher than previous estimates [12–15] (corresponding to events rates $\sim 6\%$ higher) and have raised the so-called reactor antineutrino anomaly [16]. In fact, adopting the new fluxes, the VSBL ($L \lesssim 100 \text{ m}$) reactor measurements show a clear deficit (a $\sim 3\sigma$ effect) with respect to the theoretical expectations.

Despite the effort made by the authors of [10], who have included thousands of β -branches in the calculations, the new determinations are not entirely performed with an *ab initio* procedure. In fact, approximately 10% of all the β -branches remains unknown and their contribution is accounted for by adding up a few fictitious effective β -branches. The resulting overall (electron) β spectrum is then “anchored” to that one measured by the ILL experiment [13–15] in the 1980s. Therefore, at present, a systematic error in the ILL measurement cannot be excluded as the origin of the

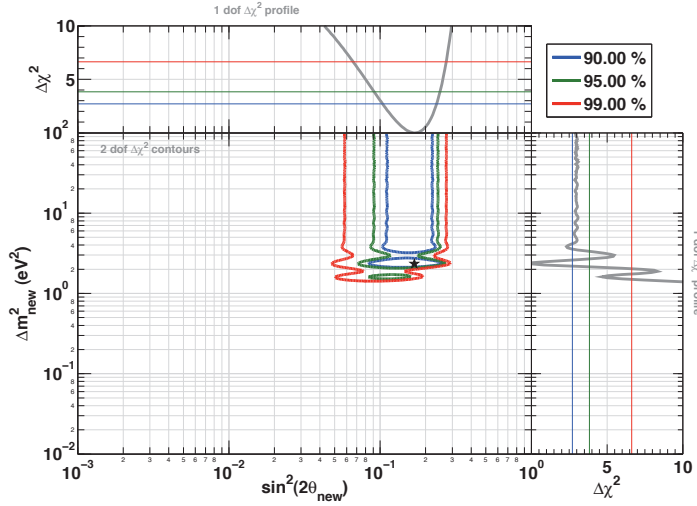


Fig. 2. Regions allowed by the combination of the reactor and gallium anomalies (figure taken from [3]).

reactor anomaly.

An apparently unrelated deficit has been evidenced in the calibration campaign conducted at the solar neutrino experiments GALLEX and SAGE [17,18] with high intensity radioactive sources. The exact statistical significance of the deficit fluctuates in the range $[2.7\sigma, 3.1\sigma]$ depending on the assumptions made on the theoretical estimate of the cross section $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$ (see the discussion presented in [18]). While the anomaly may well represent a signal of new physics other (more prosaic) possibilities remain open such as a systematic error in the Ge extraction efficiency or in the theoretical estimate of the cross-section.

Both the reactor and gallium anomalies can be interpreted in terms of a phenomenon of electron neutrino disappearance driven by sterile neutrino oscillations. The result of a combined fit of the two anomalies is shown in Fig. 2 in terms of a new mass-squared difference Δm_{new}^2 and of an effective mixing angle θ_{new} . In a 3+1 framework the following identifications hold: $\Delta m_{new}^2 \equiv \Delta m_{14}^2$ and $\sin^2 2\theta_{new} \equiv 4|U_{e4}|^2(1 - |U_{e4}|^2)$. From Fig. 2 we see that values of $\Delta m_{new}^2 \gtrsim 1 \text{ eV}^2$ and relatively large values of $\sin^2 2\theta_{new} \sim 0.17$ are preferred (corresponding to values of $|U_{e4}|^2 \sim 0.04$).

2.3. The dark radiation anomaly

The latest cosmological data analyses of the Cosmic Microwave Background (CMB) and large scale structure (LSS) [19–27], show a weak ($\sim 2\sigma$) but consolidated trend towards extra relativistic degrees of freedom at the epoch of the CMB decoupling. In Fig. 3 we report the results of the analysis performed in [20], where the number

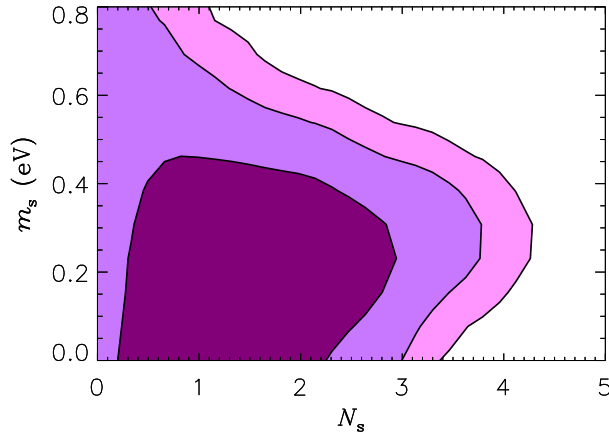


Fig. 3. Regions allowed by the CMB data. The ordinary neutrinos are assumed to be massless while the N_s sterile species have a common mass m_s (figure taken from [20]).

of extra relativistic species is denoted with N_s .

Such hint for extra radiation, often dubbed as “dark radiation”, is not in contrast with the constraints coming from the earlier epoch of big bang nucleosynthesis (BBN), which, however, allow for no more than one additional sterile species [28,29]. It must be stressed that the bounds obtained in [28,29] are obtained under the hypothesis that sterile neutrinos were in thermal equilibrium with the primeval plasma prior to BBN (more precisely prior to the decoupling of the ordinary neutrinos).

The issue of thermalization of sterile neutrinos prior to the BBN epoch has been recently reconsidered in [30,31] (for earlier works see the list of references given in [3,30]). The basic result of these works is that for the mass-mixing parameters of current interest full thermalization of one sterile neutrino do occur unless a very large ($\gtrsim 10^{-3}$) initial lepton asymmetry is present.

New information on the radiation content of the early universe is expected to come during this year from the Planck mission. Awaiting such results, one must bear in mind that the excess of radiation is not specific of sterile neutrinos since it can be produced by alternative mechanisms (see for example [32] and references therein). For this reason, a positive confirmation by Planck of the present hint would not necessarily imply the existence of sterile neutrinos, although it would certainly reinforce such an hypothesis. On the other hand, a disconfirmation of the hint, while certainly disfavoring the hypothesis of sterile neutrinos, would not be able to definitely exclude this option, since some mechanism may suppress the contribution of the sterile neutrinos to the radiation content of the early universe. Therefore, while the Planck results will give an important indication, it would be prudent to leave the final word on sterile neutrinos to dedicated laboratory oscillation experiments.

3. Do the anomalies depict a coherent picture?

The important question naturally arises as to whether the anomalies described above can be simultaneously interpreted within a consistent theoretical framework. To this purpose many analyses have been performed in the literature (see for example the overview given in [3]).

A first important conclusion derived from these works is that those models incorporating more than one sterile neutrino are disfavored at least for three reasons: I) They are incompatible with primordial nucleosynthesis [28,29]; II) They introduce an absolute neutrino mass content that cannot be tolerated by cosmological data^a (indeed, the 3+1 scheme is already borderline in such a respect); III) Differently from the past, they are no more necessary to explain (through CP violation effects) the mismatch between the neutrino and antineutrino excesses previously found in MiniBooNE, and now much reduced in the latest data release.

We are thus left with the 3+1 scheme arguably favored by Occam's razor [34], which however, has its own troubles. Indeed, interpreted in this framework, the anomalous reactor and gallium $(\bar{\nu}_e)$ -disappearance measurements point towards a non-zero value of the parameter $|U_{e4}|^2$. On the other hand, all searches of a possible $(\bar{\nu}_\mu)$ disappearance induced by sterile neutrino oscillations have given negative outcome [35–38], implying a stringent upper bound on the amplitude of $|U_{\mu4}|^2$. The different results of the $(\bar{\nu}_e)$ and $(\bar{\nu}_\mu)$ disappearance searches are perfectly consistent but (taken together) are in strong tension with the positive signal of $(\bar{\nu}_\mu) \rightarrow (\bar{\nu}_e)$ conversion found at LSND and MiniBooNE, which requires a (too large) value for the product $|U_{e4}|^2|U_{\mu4}|^2$ (see the discussion presented in [34,39]). This situation is depicted in Fig. 4, where the constraints from disappearance and appearance data are compared for the 3+1 model [40]. Adding further sterile neutrino species does not help in reducing such a tension, which indeed persists also in the more general 3+2 and 3+3 schemes (see [34,41]) .

Concerning the cosmological data, it must be noted that the bounds on the absolute mass of the new light particles lie in the sub-eV range and therefore they are in tension with the estimates coming from the laboratory anomalies, which point towards a mass-squared splitting of $\sim 1 \text{ eV}^2$ (see for example [42]).

Therefore, the (provisional) answer to the question posed above is negative, as the simultaneous interpretation of *all* the anomalous data is problematic. However, we deem it premature to abandon the sterile neutrino hypothesis on such a basis. Indeed, the possibility exists that some of the experimental results may be wrong while other being correct. We remind that the discovery of neutrino oscillations originated in a similarly confused landscape of discrepant measurements, which eventually converged in a clear (positive) picture. The same thing may happen also in the present case.

^aThis is true even if one takes into account the (small) departures from full thermalization [33].

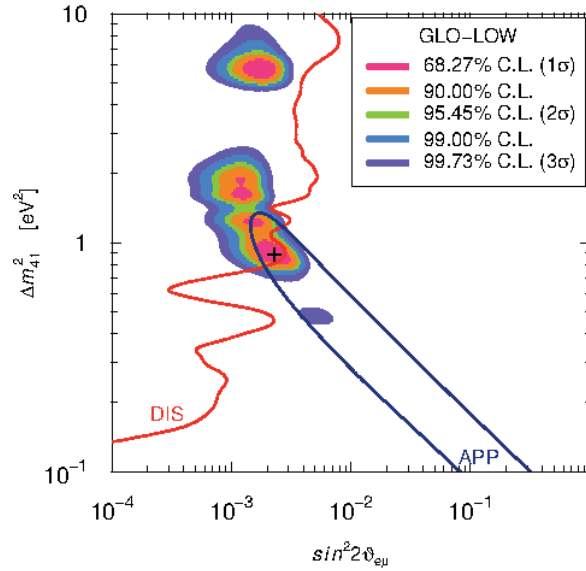


Fig. 4. The solid lines delimit the 3σ regions allowed respectively by the appearance and disappearance data, while the colored regions are those preferred by the combination of the two datasets (figure taken from [40]).

4. An independent test of the indication of $|U_{e4}|^2 > 0$

In this perspective it is essential to carefully put under test any single piece of evidence, irrespective of all the other ones. Here, we focus on the reactor and gallium anomalies, which *taken alone* are consistent with a non-zero admixture of the electron neutrino with new sterile species.

As we have shown in [43], where we have presented the analytical treatment of the solar MSW transitions in a 3+1 scheme (see also [44]), the solar sector data (Solar and KamLAND) offer a sensitive probe of the admixture of the electron neutrino with new sterile species. In a subsequent paper [45], we have shown how the first evidence for non-zero θ_{13} further improved the sensitivity of the solar sector to U_{e4} . In this review we present an updated version^b of the analysis performed in [45] by incorporating the latest (strongest) constraints on θ_{13} , which is now determined with a far better precision.

In the left panel of Fig. 5, the diagonal bands indicate the region allowed by the combined solar and KamLAND data in the plane $[\sin^2 \theta_{13}, \sin^2 \theta_{14}]$.^c We stress that the KamLAND analysis has been performed using only the spectral shape information so as to render its results independent of the reactor antineutrino flux normalization. In the same panel, the vertical bands identify the range allowed for

^bPreliminary results of this analysis have been presented in [46].

^cIn the parametrization adopted in [43, 45] $|U_{e4}|^2 \equiv \sin^2 \theta_{14}$.

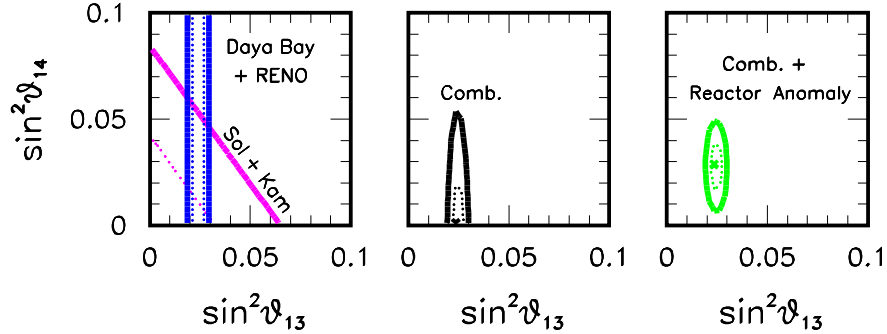


Fig. 5. Left panel: regions allowed by the solar sector data (diagonal bands) and by the dual-baseline reactor (Daya Bay and RENO) experiments (vertical bands). Middle panel: regions allowed by their combination. Right panel: combination of the constraints in the middle panel with those coming from the reactor anomaly. The contours refer to $\Delta\chi^2 = 1$ (dotted line) and $\Delta\chi^2 = 4$ (solid line).

θ_{13} by the combination of the dual-baseline reactor experiments Daya Bay [47] and RENO [48]. In order to understand this behavior, it should be observed that at distances of a few hundreds meters, typical of the near and far detectors of the dual-baseline reactor experiments, the oscillations driven by the new mass-squared splitting get completely averaged for Δm_{14}^2 in the region of current interest around $\sim 1 \text{ eV}^2$ and their effect (an energy independent suppression) is identical at the near and far sites. Therefore, the estimate of θ_{13} (based on a near/far comparison) is insensitive to θ_{14} (as well as to the reactor flux normalization). The same conclusion is not true for Double Chooz [49], currently working only with the far detector (see the discussion presented in [50]).

The superposition of the two datasets (solar+KamLAND and Daya Bay+RENO) evidences their complementarity in constraining the two mixing angles. Their combination, shown in the middle panel of Fig. 5, leads to the strong upper bound

$$\sin^2 \theta_{14} \equiv |U_{e4}|^2 < 0.041 \quad (90\% \text{ C.L.}). \quad (1)$$

As already stressed, this bound does not depend on the normalization of the reactor fluxes and thus represents an independent constraint on $|U_{e4}|^2$. Therefore, it makes sense to combine such a bound with the information coming from the reactor anomaly.^d The result of such an exercise is shown in the right panel of Fig. 5, where we have taken the reactor anomaly likelihood from [18]. The effect of the bound in Eq. (1) is a downshift of the 2σ range allowed for $|U_{e4}|^2$ from $[0.011, 0.054]$ [18] to

^dWe do not combine the bound in Eq. (1) with the constraints coming from the gallium anomaly since they are not independent. Indeed, a shift in the theoretical estimate of the cross-section $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$, which is a critical issue for the gallium anomaly, would also modify the solar bound on θ_{14} (and θ_{13}).

[0.005, 0.050], and a sensitive reduction of the overall statistical significance (from $\sim 3\sigma$ to $\sim 2.5\sigma$) of the indication of $\theta_{14} > 0$.

5. Conclusions

We have presented a concise discussion of the current phenomenology of light sterile neutrinos. The present situation appears quite confused and new experimental input is indispensable to shed light on the issue. A general consensus towards the absolute necessity to perform new and decisive experimental tests has clearly emerged within the “neutrino community”. This aspiration is documented by a “white paper” [3] coauthored by a large number of scientists (theorists, experimenters and phenomenologists) affiliated with more than one hundreds international institutions.

Such a goal requires the realization of new and more sensitive experiments, able (in case of negative outcome) to definitely rule out the sterile neutrino hypothesis, and (in case of positive outcome) provide a clear observation of the oscillatory pattern in the energy and/or space domains, which is the distinctive and indisputable signature of the flavor oscillation phenomenon.

It is important to realize that the new more sensitive experimental tests (see [3] for a comprehensive overview) will be extremely useful independently of their outcome. In case of a positive signal (evidence of sterile neutrino oscillations) we would be faced with an extraordinary discovery: new physics beyond the Standard Model would manifest in a completely unexpected form, well different from the mainstream high-energy realizations commonly investigated. On the other hand, in case of a negative result, the new experiments will be able to put a stringent upper bound on the new mass-mixing parameters, thus ruling out definitively the light sterile neutrino hypothesis as the explanation of the puzzling experimental anomalies.

Acknowledgments

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